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Innovative Integration of Hydropower and Thermal Energy for Combined Heat and Power Production: A Comprehensive Review

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ABSTRACT The urgent need for sustainable energy solutions has led to a growing interest in the innovative integration of hydropower and thermal energy systems for combined heat and power (CHP) production. This comprehensive review examines the current state of integration techniques, assessing their technical, economic, and environmental implications. Hydropower, as a renewable resource, provides a reliable and flexible energy supply, while thermal energy systems enhance overall efficiency and energy security. By synergizing these two energy sources, the integration maximizes resource utilization and addresses the intermittent nature of renewable energy. This review highlights the role of such integrated systems in contributing to global sustainability goals, including the United Nations Sustainable Development Goals (SDGs), particularly Goal 7 (Affordable and Clean Energy) and Goal 13 (Climate Action). The findings indicate that hydropower-thermal integration can achieve greenhouse gas emissions reductions of up to 30%, significantly improving energy efficiency by 20-30% compared to conventional systems. Furthermore, integrating these systems can lead to cost savings of approximately 15-25% in operational expenses, primarily through enhanced fuel utilization and reduced reliance on fossil fuels. Through an analysis of case studies and recent advancements in technology, this review offers valuable insights for policymakers, researchers, and industry stakeholders aiming to implement sustainable energy solutions. By embracing innovative integration approaches, we can pave the way for a more resilient and sustainable energy future.

Keywords: Hydropower; Thermal Energy; Combined Heat and Power (CHP); Energy Integration; Renewable Energy; Sustainability Goals; Greenhouse Gas Emissions

I. INTRODUCTION

Combined heat and power (CHP) systems are integrated energy solutions that simultaneously generate electricity and useful heat from a single fuel source, enhancing overall energy efficiency and reducing greenhouse gas emissions compared to conventional generation methods [1, 2]. These systems can be categorized based on their thermodynamic cycles, including Rankine, Stirling, and gas turbine cycles, each offering varying efficiencies and applications. CHP systems are particularly beneficial in settings requiring both low-grade heat and high-grade power, such as hospitals and universities, where they can significantly lower operational costs and energy consumption [3, 4]. Additionally, advancements in fuel cell technology, particularly proton membrane fuel cells (PEMFCs) and solid oxide fuel cells (SOFCs), have expanded the potential of CHP systems by improving net efficiency through effective heat Utilization [5]. The integration of renewable energy sources and innovative designs further positions CHP systems as a sustainable solution for future energy needs[6].

Integrating renewable energy sources, particularly hydropower, with thermal energy systems is crucial for enhancing energy stability and reducing greenhouse gas emissions. The hybridization of these systems addresses the intermittent nature of renewable sources like wind and solar, which can lead to power quality issues and operational Challenges. By combining hydropower with thermal systems, such as gas turbines or boilers, energy storage solutions can be optimized, ensuring a reliable power supply while minimizing reliance on fossil Fuels [7-9]. Furthermore, pumped storage hydropower plants can effectively mitigate the variability of renewable sources, demonstrating lower water losses compared to traditional thermal power plants. This integrated approach not only supports a low-carbon energy transition but also enhances the overall efficiency and resilience of energy systems, making it a vital strategy for sustainable energy development[10] [11].

This paper provides useful insights for policymakers, researchers, and industry stakeholders looking to implement sustainable energy solutions through an analysis of case studies and recent technological breakthroughs. We can create a more robust and sustainable energy future by adopting creative integration strategies.

II. TECHNOLOGICAL FOUNDATIONS AND INTEGRATION CONCEPTS

Hydropower is recognized as a highly efficient and reliable renewable energy source, contributing approximately 17% to the global electricity supply, which is nearly double that of all other renewable combined. Its technology has evolved significantly since the 19th century, with modern systems like pumped storage hydropower (PSH) achieving operational efficiencies of up to 60.78%. The performance of hydropower plants is influenced by factors such as waterfall height and turbine design, with studies indicating that optimal configurations can enhance power output and efficiency. Furthermore, hydropower plays a crucial role in stabilizing energy systems, supporting the integration of variable renewable like wind and solar, and reducing greenhouse gas emissions[12]. However, the development of hydropower must consider environmental impacts and climate change resilience to ensure sustainable management and operation [13-15]. Hydropower, while recognized for its potential to provide flexible energy solutions, faces significant limitations that can hinder its ability to meet diverse heat and power needs.

Environmental constraints, such as those imposed by the EU's Water Framework Directive, can reduce operational flexibility and production income, as demonstrated in studies from Norway and Sweden. Additionally, the integration of variable renewable energy sources like wind and solar increases the demand for hydropower flexibility, yet operational conflicts arise when hydropower facilities are tasked with balancing these fluctuations while adhering to ecological and policy requirements. Furthermore, social and environmental impacts, particularly in developing regions, pose challenges to hydropower development, complicating its role as a reliable energy source. Thus, while hydropower can contribute to grid stability, its effectiveness is often constrained by external factors and operational conflicts[16, 17].

First, we will discuss Run-of-river (ROR) hydropower systems that utilize the natural flow of rivers to generate electricity. As shown in (Fig. 1) presents a sustainable alternative with minimal environmental impact compared to traditional hydropower methods. In Great Britain, the hydrological potential for ROR is estimated at 20 GW, with a realizable potential of 290 to 320 MW, primarily from mini and small schemes located in less populated areas[18]. However, these systems face challenges in optimizing power generation due to their limited storage capacity, which necessitates innovative control strategies to enhance efficiency and stability. Recent advancements, such as the HYPER-FORD toolbox, have improved design optimization while significantly reducing computational costs, thus promoting sustainability by minimizing associated greenhouse gas emissions. Furthermore, regulatory frameworks, particularly abstraction licenses, can influence power generation potential, with optimal policies potentially increasing future generation by over 30% in some regions[19]. Overall, ROR hydropower represents a viable and environmentally friendly energy source, contingent on effective management and regulatory support.

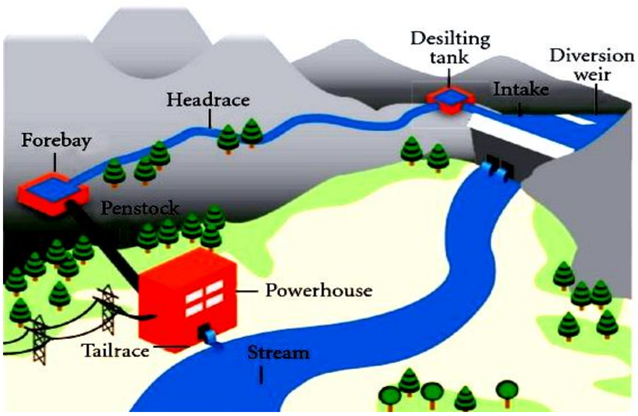

Fig. 1: Run-of-river (ROR) hydropower system

Second is Pumped-storage hydropower (PSH) which plays a crucial role in energy storage and grid stability, particularly as the share of renewable energy sources increases. As shown in (Fig. 2). PSH accounts for 90% of global energy storage capacity, providing essential flexibility to balance supply and demand during peak periods. Its ability to store excess energy generated from intermittent sources like wind and solar enhances grid reliability and operational efficiency. Moreover, PSH systems can reduce costs and promote energy self-sufficiency, especially in agricultural settings, by allowing farms to generate their electricity and sell surplus power back to the grid. Financial viability can be improved by integrating existing conventional hydropower resources, which lowers the levelized cost of energy storage. Innovative designs, such as multi-reservoir systems utilizing seawater, further expand the potential applications of PSH in achieving sustainable energy goals [20-22]. Overall, PSH is integral to a resilient and flexible energy future.

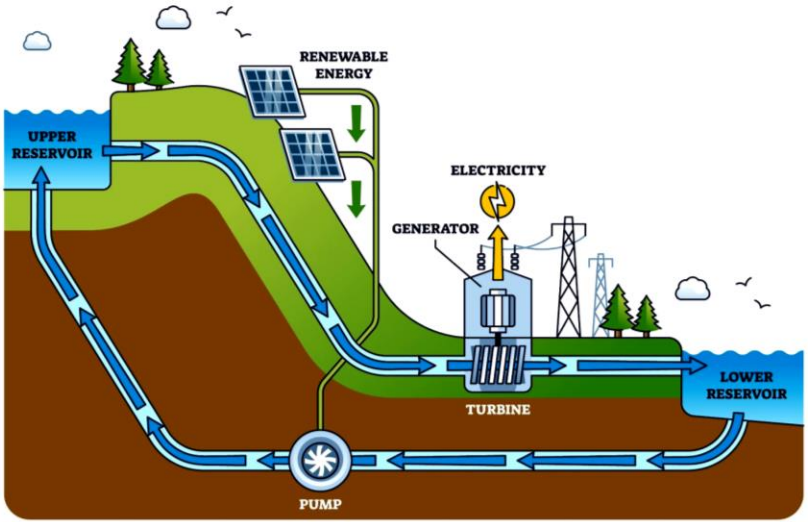

Fig. 2: Pumped-storage hydropower system

Gas Combined Cycle (GCC) systems integrate gas turbines with steam turbines to enhance overall efficiency, achieving net power plant efficiencies exceeding 64% with natural gas as fuel. The combination allows for the recovery of waste heat from the gas turbine, which is then utilized to generate steam that drives the steam turbine, thereby maximizing energy output from the same fuel input. As shown in (Fig. 3). This dual-cycle approach not only improves efficiency but also positions GCCs as economically better solutions for electricity generation due to their lower emissions and operational flexibility[23, 24]. Challenges in commissioning and operational integration, such as the coupling of steam and gas turbines, have been documented, highlighting the need for precise control systems to manage the complex interactions between the two turbine types. Furthermore, advancements in technology and the potential incorporation of energy storage systems can further optimize the operational efficiency of GCCs, addressing issues related to non-linear cost curves in electricity markets[25, 26].

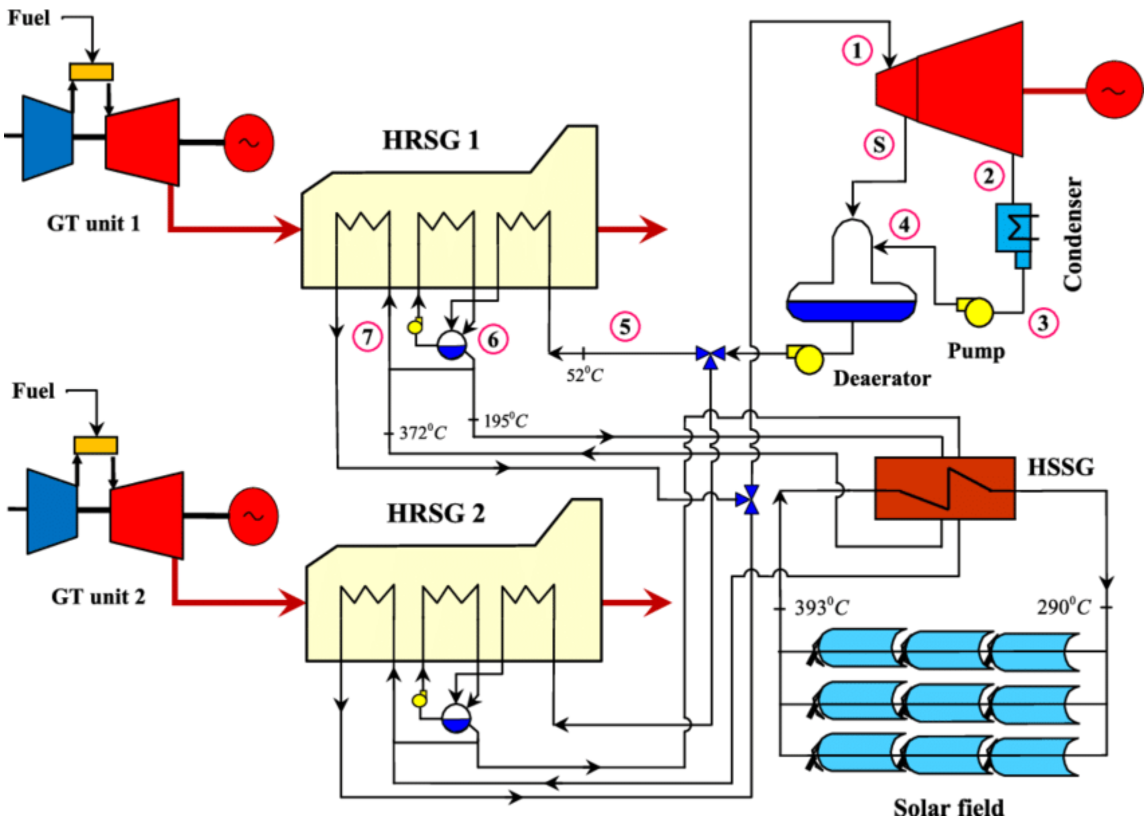

Fig. 3: Combined cycle power plant model

Biomass and waste heat recovery systems are increasingly recognized for their potential to enhance energy efficiency and sustainability. Various technologies, such as thermoelectric generator (TEG) systems, have been developed to effectively harvest waste heat from biomass engines, achieving notable performance improvements by minimizing thermal resistances. As shown in (Fig. 4). Additionally, aerobic and anaerobic digestion techniques facilitate the conversion of biomass waste into bio-energy, contributing to a circular economy by recovering valuable resources and reducing environmental impact[27, 28]. The integration of absorption heat pumps in biomass cogeneration plants has demonstrated significant operational flexibility and energy savings, enhancing thermoelectric output by 13.2%. Furthermore, innovative tri-generation systems utilizing biomass can simultaneously produce power, heat, and hydrogen, achieving energy efficiencies exceeding 57%. Lastly, bio-drying processes in biomass power plants have been shown to reduce energy requirements significantly, further emphasizing the importance of waste heat recovery in optimizing biomass Utilization.

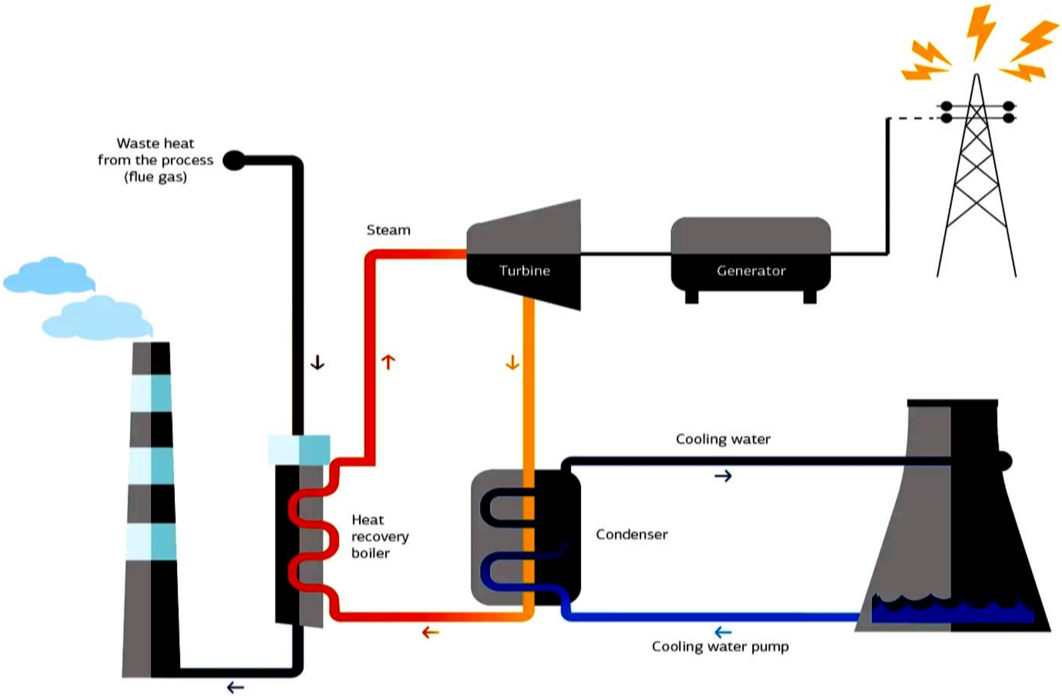

Fig. 4: Heat waste recovery system

Geothermal energy, when combined with hydropower, presents a promising solution for providing base load thermal energy in select regions, leveraging the strengths of both renewable sources. Geothermal energy is recognized for its reliability and ability to deliver consistent power, contributing significantly to energy independence and sustainability, with the potential for multi-generation applications such as power generation and seawater desalination. As shown in (Fig. 5). While hydropower currently dominates the renewable energy landscape, accounting for approximately 48% of global capacity, geothermal energy remains underutilized, representing only about 0.5%. However, advancements in technology and supportive policy frameworks could enhance the efficiency and deployment of geothermal systems, making them integral to future energy mixes alongside hydropower[29, 30]. This synergy could address both energy demands and environmental concerns, fostering a more sustainable energy future.

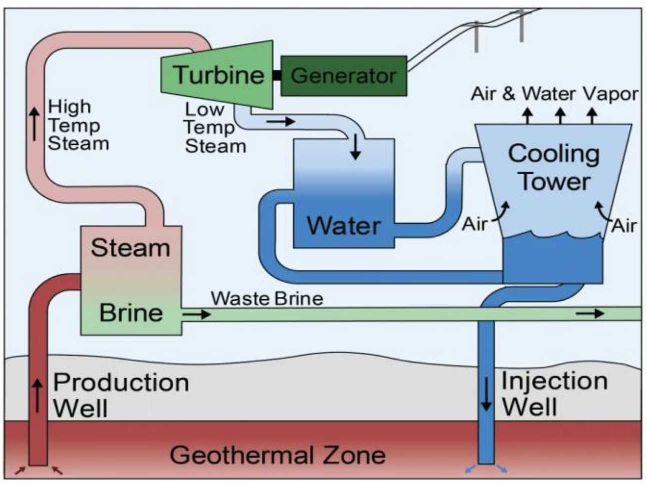

Fig. 5: Geothermal energy system

Cascading systems in energy production, particularly hydropower and thermal systems, exemplify the integration of renewable and supplementary energy sources. Hydropower plants utilize cascading turbines to efficiently convert the kinetic energy of flowing water into electricity, optimizing water flow management and minimizing environmental impact. Additionally, hydroelectric cogeneration systems enhance this process by utilizing exhaust steam from thermal systems, such as coal-fired power plants, to generate electricity and provide heat for desalination, thereby improving overall system efficiency. The concept of cascading extends beyond energy generation; it also encompasses the potential for cascading impacts in climate change scenarios, highlighting the interconnectedness of human-environment systems and the need for robust methodologies to assess these interactions. Furthermore, cascading bio-energy systems illustrate the integration of biological and thermochemical technologies for sustainable biofuel production, emphasizing the importance of resource efficiency in energy systems[31, 32]. Thus, cascading systems represent a multifaceted approach to energy production and resource management.

Cogeneration systems, also known as combined heat and power (CHP) systems efficiently produce both thermal and electrical energy from a single fuel source, significantly enhancing energy efficiency compared to separate generation methods. These systems are particularly beneficial in industrial settings, such as chemical and steel production, where simultaneous heat and power are essential. Recent advancements include integrating renewable energy sources and energy storage, which further optimize cogeneration efficiency and reduce reliance on fossil fuels[33, 34]. As shown in (Fig 6) additionally, the application of Power-to-Heat technologies in district heating systems, as demonstrated in Sofia, illustrates the potential for hybrid systems to displace gas demand and improve overall energy management. Furthermore, the integration of industrial waste heat into district heating networks presents opportunities for enhanced energy utilization, although challenges remain in data availability and system coupling. Overall, cogeneration systems represent a pivotal strategy for achieving sustainable energy and environmental goals.

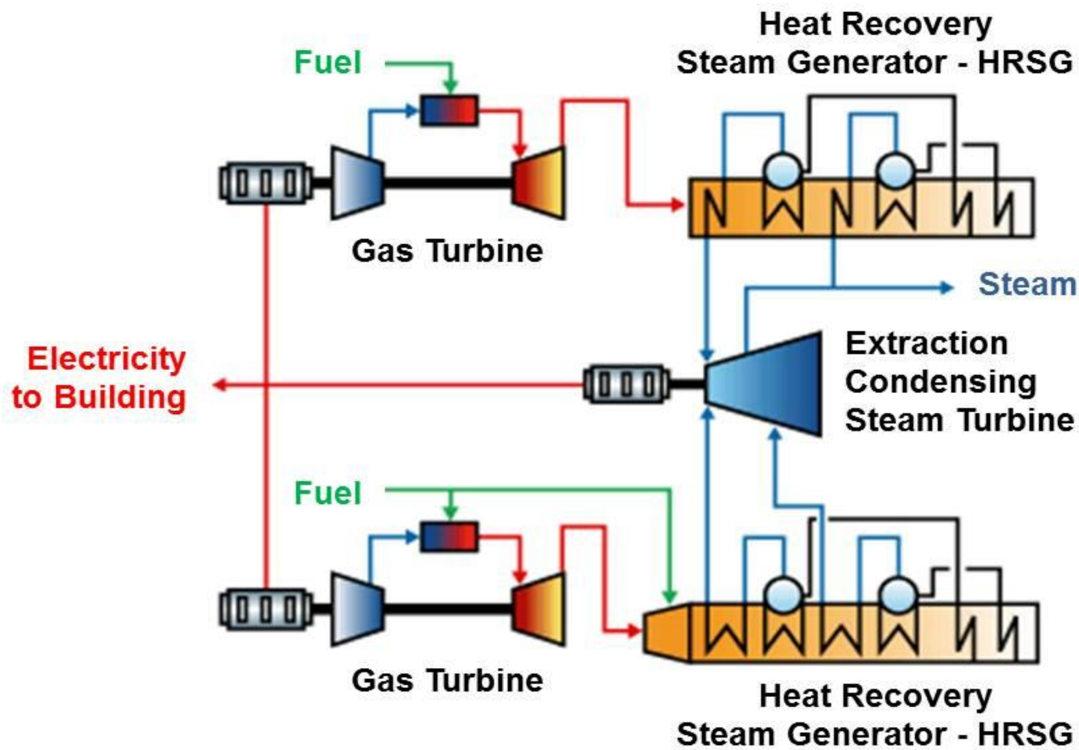

Fig. 6: CHP system arrangement example of incorporating combustion turbine and generator set with the turbine exhaust recovered

Smart grid integration plays a crucial role in optimizing power and heat distribution in real time, effectively balancing supply and demand. By leveraging modern information and communication technologies, smart grids facilitate dynamic monitoring and control of energy production and consumption, enhancing overall system resilience and efficiency. The incorporation of demand flexibility, particularly through technologies like heat pumps and electric vehicles, allows for better management of intermittent renewable energy sources, ensuring that both heat and electric demands are met efficiently. Additionally, decentralized control methods utilizing agent-based systems optimize microgrid operations, leading to significant cost reductions and improved performance in energy distribution. Furthermore, load flow analysis demonstrates that integrating distributed generation and intelligent control systems enhances voltage regulation and system stability, underscoring the necessity of smart grid technologies in modern power systems[35].

III. Benefits of Hybrid Hydropower-Thermal CHP Systems

Hybrid Hydropower-Thermal Combined Heat and Power (CHP) systems effectively utilize both electricity and thermal energy through various innovative strategies. The integration of heat recovery (HR) and thermal load control (TLC) significantly enhances the efficiency of these systems, as demonstrated in studies where these strategies reduced costs and emissions while increasing renewable energy utilization[36]. Additionally, the use of proton exchange membrane fuel cells (PEMFC) in CHP systems showcases high electrical generation efficiency and the potential to recover substantial amounts of thermal energy, thus addressing power shortages while minimizing waste. Furthermore, thermoacoustic micro-CHP systems illustrate the effective recovery of low-grade thermal energy, achieving high exergy efficiency and substantial annual energy savings and emissions reductions. Collectively, these approaches highlight the potential of hybrid systems to optimize energy use and contribute to sustainable energy solutions[37].

The integration of renewable hydropower and thermal sources, such as biomass, significantly reduces reliance on fossil fuels and mitigates carbon footprints. Renewable energy sources, including hydropower, solar, and biomass, can potentially eliminate up to 90% of carbon emissions from electricity generation by 2050, addressing over 75% of global greenhouse gas emissions attributed to fossil fuels. As shown in (Fig. 7). Biomass, in particular, offers a sustainable alternative by utilizing waste bio-resources, which not only generate energy but also absorb carbon dioxide during photosynthesis, thereby lowering greenhouse gas emissions. Additionally, the combination of biomass and solar thermal systems has been shown to reduce environmental impacts by approximately 43% compared to conventional fossil fuel systems, highlighting the effectiveness of these renewable technologies in achieving energy efficiency and sustainability in residential applications. Overall, the transition to renewable energy sources is crucial for combating global warming and fostering a cleaner energy future [38].

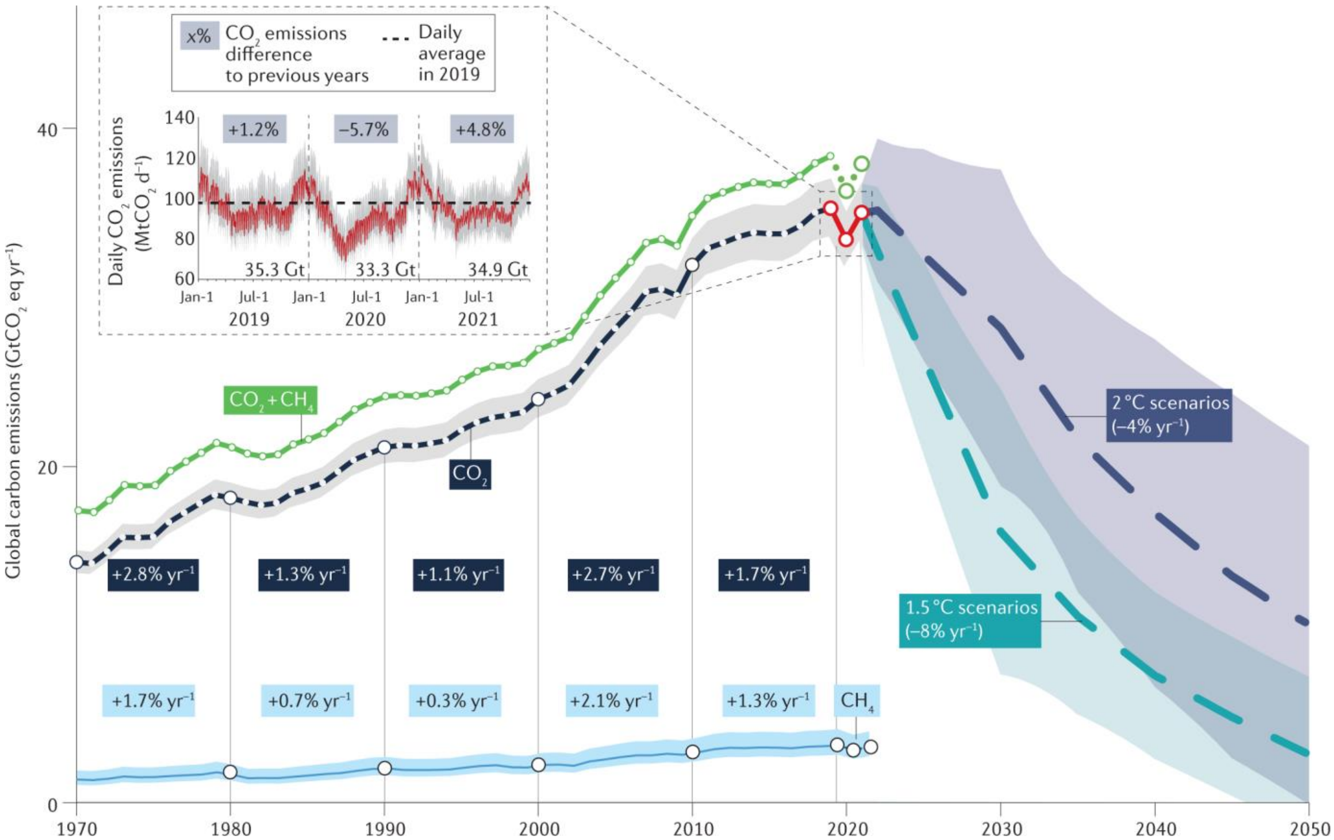

Fig. 7: worldwide CO2and CH4 Emissions for the past years [46]

Through efficient resource use and operating tactics, hybrid hydropower-thermal combined heat and power (CHP) systems dramatically lower fuel costs and increase profitability. Simulations demonstrate that the cost of power from RES is lower while considering health and environmental effects from thermal emissions, demonstrating that integrating RES with thermal plants decreases lifecycle costs and environmental consequences. Furthermore, despite an increase in capital expenses, a two-layer optimization model showed that expanding the use of renewable energy can boost the efficiency of fossil fuels and generate income from surplus electricity sales[39]. Additionally, it has been demonstrated that incorporating heat recovery and thermal load control techniques into CHP systems can lower expenses by as much as 25% while raising the proportion of renewable energy, improving overall economic performance. Overall, these systems use resource management and strategy optimization to optimize profitability while reducing operating expenses[40].

IV. CHALLENGES WE MUST OVERCOME

The integration of various energy sources and the requirement for advanced optimization approaches lead to the complexity of system design for hybrid hydropower-thermal combined heat and power (CHP) systems. As shown in (Fig. 8) The difficulties of integrating hydropower with thermal and renewable components are demonstrated by hybrid systems, like the Magat HYPP in the Philippines, which necessitate rigorous regulatory compliance and creative energy management systems to maximize efficiency and income generation[41]. Furthermore, to reduce costs and emissions, the design and operational management of these systems require sophisticated optimization models, such as two-layer stochastic techniques that consider uncertainty in renewable energy and load demands. Because it entails managing start-up costs and operating restrictions that cannot be resolved by conventional approaches, the integration of mixed integer programming for hydro and thermal plants further complicates the planning process. The complex character of these energy solutions is highlighted by the need to balance operating efficiency, regulatory requirements, and environmental implications in the design of an effective hybrid system.

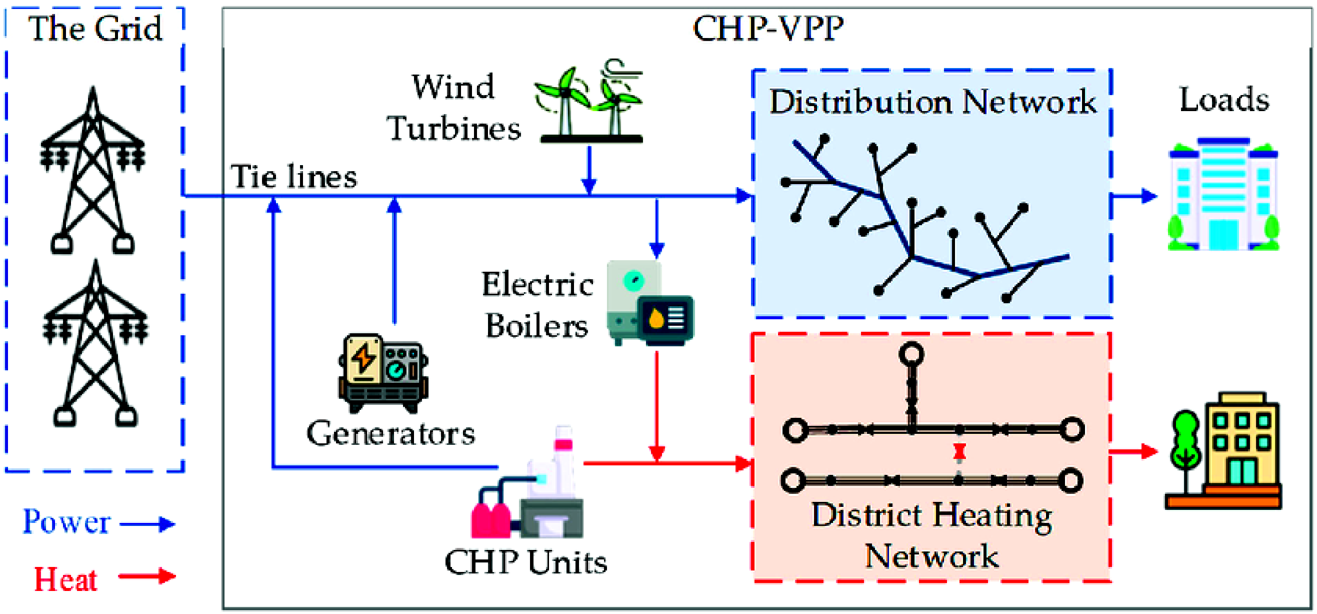

Fig. 8: Complexity of combined heat and power CHP system [45].

Advanced techniques that integrate various energy sources and maximize their interactions are required for the design and coordination of complex systems for hydropower and thermal energy in combined heat and power (CHP) generation. To efficiently meet consumer demands using a variety of energy carriers, such as natural gas and electricity from renewable sources, the idea of energy hubs (EH) makes it easier to plan electrical and thermal networks simultaneously. Furthermore, scheduling CHP systems can be greatly improved by combining pumped storage hydropower (PSH) with wind and PV systems. This lowers carbon emissions and operating expenses while enhancing the use of renewable energy sources[42]. Moreover, a multiparametric programming technique improves the operational efficiency of CHP systems by enabling the unification of design, scheduling, and control strategies across several time scales. Overall, resolving the intricate restrictions present in power system scheduling requires efficient coordination between hydro-thermal-gas systems.

The use of thermal energy and hydropower for combined heat and power (CHP) generation is severely hampered by their high capital costs and dependence on government subsidies. CHP systems require a significant initial investment, which frequently calls for financial assistance in the form of tax credits or subsidies to make projects financially feasible[43]. For example, research found that a 16% subsidy was necessary for new CHP plants in Finland to be profitable. Additionally, these difficulties are made worse by market opposition and regulatory restrictions, especially from utilities, which can make it more difficult to install and run decentralized CHP systems[44]. The overall effectiveness of federal measures to increase CHP implementation through better data collecting and supportive legislation depends on continued government support and the removal of regulatory barriers. Therefore, the potential of CHP technologies can go mostly unrealized if these financial and legal obstacles are not addressed.

V. CONCLUSION

A viable way to improve the effectiveness, dependability, and sustainability of energy generation is to combine hydropower and thermal energy systems for the production of Combined Heat and Power (CHP). Hybrid systems can optimize energy utilization and enhance grid stability by fusing the adaptability of thermal power with the renewable, low-emission advantages of hydropower. Compared to conventional fossil-fuel plants, these systems can help reduce greenhouse gas emissions, reduce waste through heat recovery, and lessen the unpredictability of renewable energy sources like solar and wind. They also provide increased operating efficiency and possible cost savings, especially when hydropower is combined with greener fuels like biomass or natural gas. However, there are obstacles to the adoption of hybrid hydropower-thermal CHP systems, including high initial costs, technical complexity, and problems with water availability for hydropower generation. These hybrid systems are becoming increasingly practical and affordable despite these obstacles thanks to developments in energy storage, smart grid technology, and digital control systems. Hybrid hydropower-thermal systems have the potential to be a key component of the global shift to a more resilient and sustainable energy future, helping to meet rising energy demands while minimizing environmental impact, provided that supportive policy frameworks, financial incentives, and ongoing technological innovation are in place.

REFERENCES:

[1] M. M. El-Sheekh, A. A. El-Nagar, M. ElKelawy, and H. A.-E. Bastawissi, "Bioethanol from wheat straw hydrolysate solubility and stability in waste cooking oil biodiesel/diesel and gasoline fuel at different blends ratio," Biotechnology for Biofuels and Bioproducts, vol. 16, p. 15, 2023/02/01 2023.

[2] M. M. El-Sheekh, A. A. El-Nagar, M. ElKelawy, and H. A.-E. Bastawissi, "Maximization of bioethanol productivity from wheat straw, performance and emission analysis of diesel engine running with a triple fuel blend through response surface methodology," Renewable Energy, vol. 211, pp. 706-722, 2023/07/01/ 2023.

[3] M.-A. Hessami, "DESIGNING A CHP SYSTEM FOR A MULTI-FUNCTION APPLICATION," in Energy and Environment, 1995, ed: Begell House, 1996.

[4] A. M. Elbanna, X. Cheng, C. Yang, M. Elkelawy, and H. Alm-Eldin Bastawissi, "Investigative research of diesel/ethanol advanced combustion strategies: A comparison of Premixed Charge Compression Ignition (PCCI) and Direct Dual Fuel Stratification (DDFS)," Fuel, vol. 345, p. 128143, 2023/08/01/ 2023.

[5] J. G. Vaghasia, J. K. Ratnadhariya, H. Panchal, K. K. Sadasivuni, D. Ponnamma, M. Elkelawy, et al., "Experimental performance investigations on various orientations of evacuated double absorber tube for solar parabolic trough concentrator," International Journal of Ambient Energy, vol. 43, pp. 492-499, 2022/12/31 2022.

[6] C. Dobre, M. Costin, and M. Constantin, "A Review of Available Solutions for Implementation of Small–Medium Combined Heat and Power (CHP) Systems," Inventions, vol. 9, p. 82, 2024.

[7] M. Elkelawy, A. Kamel, A. Abou-lazied, and S. M. El-malla, "Experimental investigation of the effects of using biofuel blends with conventional diesel on the performance, combustion, and emission characteristics of an industrial burner," Egyptian Sugar Journal, vol. 19, pp. 44-59, 2022.

[8] A. E. Kabeel, M. Elkelawy, H. A.-E. Mohamad, A. M. Elbanna, H. Panchal, M. Suresh, et al., "The influences of loading ratios and conveying velocity on gas-solid two phase flow characteristics: a comprehensive experimental CFD-DEM study," International Journal of Ambient Energy, vol. 43, pp. 2714-2726, 2022/12/31 2022.

[9] A. Mohammed Elbanna, C. Xiaobei, Y. Can, M. Elkelawy, H. Alm-Eldin Bastawissi, and H. Panchal, "Fuel reactivity controlled compression ignition engine and potential strategies to extend the engine operating range: A comprehensive review," Energy Conversion and Management: X, vol. 13, p. 100133, 2022/01/01/ 2022.

[10] U. Eswaran, "Integrating Renewable Energy Sources Into Existing Energy Systems for Achieving a Low-Carbon Energy Transition," in Sustainable Science and Intelligent Technologies for Societal Development, ed: IGI Global, 2023, pp. 262-277.

[11] M. Elkelawy, E. A. El Shenawy, H. A. E. Bastawissi, and I. A. El Shennawy, "The effect of using the WCO biodiesel as an alternative fuel in compression ignition diesel engine on performance and emissions characteristics," Journal of Physics: Conference Series, vol. 2299, p. 012023, 2022/07/01 2022.

[12] Å. Killingtveit, "Living with climate change—Hydropower," in Living with Climate Change, ed: Elsevier, 2024, pp. 423-448.

[13] M. Elkelawy, H. Alm ElDin Mohamad, A. K. Abdel-Rahman, A. Abou Elyazied, and S. Mostafa El Malla, "Biodiesel as an Alternative Fuel in Terms of Production, Emission, Combustion Characteristics for Industrial Burners: a Review," Journal of Engineering Research, vol. 6, pp. 45-52, 2022.

[14] M. Elkelawy, H. Alm ElDin Mohamad, M. Samadony, A. M. Elbanna, and A. M. Safwat, "A Comparative Study on Developing the Hybrid-Electric Vehicle Systems and its Future Expectation over the Conventional Engines Cars," Journal of Engineering Research, vol. 6, pp. 21-34, 2022.

[15] M. Elkelawy, H. A.-E. Bastawissi, A. M. Radwan, M. T. Ismail, and M. El-Sheekh, "Chapter 15 - Biojet fuels production from algae: conversion technologies, characteristics, performance, and process simulation," in Handbook of Algal Biofuels, M. El-Sheekh and A. E.-F. Abomohra, Eds., ed: Elsevier, 2022, pp. 331-361.

[16] A. R. Fernandez, S. A. Blumsack, and P. M. Reed, "Operational constraints and hydrologic variability limit hydropower in supporting wind integration," Environmental Research Letters, vol. 8, p. 024037, 2013.

[17] M. Elkelawy, H. Alm ElDin Mohamad, E. Abd Elhamid, and M. A. El-Gamal, "A Critical Review of the Performance, Combustion, and

Emissions Characteristics of PCCI Engine Controlled by Injection Strategy and Fuel Properties," Journal of Engineering Research, vol. 6, pp. 96-110, 2022.

[18] A.-D. Golgojan, C. J. White, and D. Bertram, "An assessment of run of river hydropower potential in Great Britain," in Proceedings of the Institution of Civil Engineers-Water Management, 2024, pp. 1-20.

[19] R. J. Dallison and S. D. Patil, "Run-of-river hydropower in the UK and Ireland: the case for abstraction licences based on future flows," Environmental Research: Infrastructure and Sustainability, vol. 3, p. 045005, 2023.

[20] M. R. Legacy, E. Van Wyk, and J. Brinkerhoff, "Pumped Hydro Energy Storage: A Multi-Reservoir Continuous Supply Hydroelectric Generation and Storage System," in 2024 IEEE Electrical Energy Storage Application and Technologies Conference (EESAT), 2024, pp. 1-4.

[21] A. E. Kabeel, M. Elkelawy, H. A. E. Bastawissi, and A. M. Elbanna, "An experimental and theoretical study on particles-in-air behavior characterization at different particles loading and turbulence modulation," Alexandria Engineering Journal, vol. 58, pp. 451-465, 2019/06/01/ 2019.

[22] S. El-din H. Etaiw, M. Elkelawy, I. Elziny, M. Taha, I. Veza, and H. Alm-Eldin Bastawissi, "Effect of nanocomposite SCP1 additive to waste cooking oil biodiesel as fuel enhancer on diesel engine performance and emission characteristics," Sustainable Energy Technologies and Assessments, vol. 52, p. 102291, 2022/08/01/ 2022.

[23] R. W. Smith, "Steam turbine cycles and cycle design optimization: Combined cycle power plants," in Advances in steam turbines for modern power plants, ed: Elsevier, 2022, pp. 61-102.

[24] M. ElKelawy, H. A.-E. Bastawissi, E.-S. A. El-Shenawy, H. Panchal, K. Sadashivuni, D. Ponnamma, et al., "Experimental investigations on spray flames and emissions analysis of diesel and diesel/biodiesel blends for combustion in oxy-fuel burner," Asia-Pacific Journal of Chemical Engineering, vol. 14, p. e2375, 2019.

[25] F. Wang, R. Ebarb, H. Morales, O. Lavrova, Y. Jiang, L. Sun, et al., "Leveraging Energy Storage Resources to Improve Combined Cycle Gas Turbines Operational Efficiency," in 2022 IEEE Power & Energy Society General Meeting (PESGM), 2022, pp. 01-05.

[26] M. Elkelawy, "Experimental Investigation of Intake Diesel Aerosol Fuel Homogeneous Charge Compression Ignition (HCCI) Engine Combustion and Emissions," Energy and Power Engineering, vol. Vol.06No.14, p. 14, 2014.

[27] A. Sana, A. Mahmood, and M. Ibrahim, "Recovery of resources and circular economy from biomass-derived waste through aerobic and anaerobic digestion-based technique," in Nanomaterials in Biomass Conversion, ed: Elsevier, 2024, pp. 411-463.

[28] H. A.-E. Bastawissi and M. Elkelawy, "Investigation of the Flow Pattern inside a Diesel Engine Injection Nozzle to Determine the Relationship between Various Flow Parameters and the Occurrence of Cavitation," Engineering, vol. Vol.06No.13, p. 13, 2014.

[29] B. Bouacem and K. Jaouadi, "Comparative analysis of geothermal and hydropower as sustainable energy solutions."

[30] J.-z. Yu, Z. Yu-Sheng, M. Elkelawy, and Q. Kui, "Spray and combustion characteristics of HCCI engine using DME/diesel blended fuel by port-injection," SAE Technical Paper 2010-01-1485, 2010.

[31] D. Kraljić and M. Desmarais, "Cascading bioenergy systems for sustainable biofuel production by integrating biological and thermochemical technologies," in Waste Biorefinery, ed: Elsevier, 2021, pp. 475-489.

[32] H. A. El-Din, M. Elkelawy, and Z. Yu-Sheng, "HCCI engines combustion of CNG fuel with DME and H 2 additives," SAE Technical Paper 2010-01-1473, 2010.

[33] A. V. M. Rao and A. K. Singh, "Cogeneration Plants Design Optimization by Integrating Them with Renewable Energy Towards Sustainable Energy and Environmental Security," in 2023 International Conference on Intelligent and Innovative Technologies in Computing, Electrical and Electronics (IITCEE), 2023, pp. 976-981.

[34] M. Elkelawy, Z. Yu-Sheng, A. E.-D. Hagar, and J.-z. Yu, "Challenging and Future of Homogeneous Charge Compression Ignition Engines; an Advanced and Novel Concepts Review," Journal of Power and Energy Systems, vol. 2, pp. 1108-1119, 2008.

[35] N. Alamoudi, F. Baqais, L. Mustafa, and E. Barakat, "Load Flow Analysis and Optimization for Smart Grid Integration in Power Systems," in 2024 21st Learning and Technology Conference (L&T), 2024, pp. 127-132.

[36] M. R. Maghami, A. G. O. Mutambara, C. Gomes, and J. Pasupuleti, "Impact of heat recovery and thermal load control on combined heat and power (CHP) performance," Energy Conversion and Management, vol. 307, p. 118388, 2024.

[37] H. Wang, C. Gu, X. Zhang, and F. Li, "Optimal CHP planning in integrated energy systems considering network charges," IEEE Systems Journal, vol. 14, pp. 2684-2693, 2019.

[38] T. S. Ustun, "Carbon Footprint Reduction in Energy Sector with Higher Penetration of Renewable Energy Resources," 2024.

[39] H. Liu, Z. Miao, N. Wang, and Y. Yang, "A two-layer optimization of design and operational management of a hybrid combined heat and power system," Frontiers in Energy Research, vol. 10, p. 959774, 2022.

[40] P. T. Ha, D. T. Tran, T. M. Phan, and T. T. Nguyen, "Maximization of total profit for hybrid hydro-thermal-wind-solar power systems considering pumped storage, cascaded systems, and renewable energy uncertainty in a real zone, Vietnam," Sustainability, vol. 16, p. 6581, 2024.

[41] H. Nøvik, E. Krogh, M. K. Stokke, E. S. Marstein, J. Kong, and D. H. Ramos, "The challenge of a real, complex hybrid project," 2023.

[42] S. Zhu, E. Wang, S. Han, and H. Ji, "Optimal scheduling of combined heat and power systems integrating hydropower-wind-photovoltaic-thermal-battery considering carbon trading," IEEE Access, 2024.

[43] E. Thorin, J. Sandberg, and J. Yan, "Combined heat and power," 2015.

[44] V. P. D. S. Kusch-Brandt, "COMMON CHALLENGES IN THE IMPLEMENTATION OF DECENTRALIZED COMBINED HEAT AND POWER PRODUCTION (CHP)," in 18th International Multidisciplinary Scientific GeoConferences SGEM 2018, 2018, pp. 219-226.

[45] Wang, J.; Pan, Z.; Li, S.; Ge, H.; Yang, G.; Wang, B. Optimal Scheduling of Virtual Power Plant Considering Reconfiguration of District Heating Network. *Electronics* 2023, *12*, 3409. https://doi.org/10.3390/electronics12163409

[46] Liu, Z., Deng, Z., Davis, S.J. et al. Monitoring global carbon emissions in 2021. Nat Rev Earth Environ 3, 217–219 (2022). https://doi.org/10.1038/s43017-022-00285-w